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# AEROACOUSTIC PREDICTION OF THE LAGOON LANDING GEAR

**Túlio R. Ricciardi**
**William R. Wolf**
Universidade Estadual de Campinas, UNICAMP
tulioricci@fem.unicamp.br
wolf@fem.unicamp.br
**Rachelle Speth**
The Boeing Company, St. Louis, EUA

***Abstract.*** *This paper presents detached eddy simulations, DES, of the LAGOON landing gear configuration performed using different unstructured meshes. We employ the BCFD code for the DES calculations and results are compared to experimental measurements available in the literature. An implicit dual-time stepping method is employed together with an optimized second-order backward-differencing scheme. For the spatial discretization, a second order accurate HLLE scheme is employed together with a bounded central differencing approach to reduce numerical dissipation of the flux reconstruction. Results are presented in terms of steady and unsteady hydrodynamic data on the surface and along the wake. Finally, with the proper orthogonal decomposition, POD, of the unsteady flow field, it is possible to identify coherent energetic structures responsible for the noise generation at 1.5kHz observed in the experiments.*

***Keywords:*** *Landing gear noise, modal decomposition, reduced order model*

## 1. INTRODUCTION

Civilian aviation is projected to grow over the forthcoming years, but the continued growth is critically dependent on managing its environmental impact. Currently, aircraft noise is considered one of the most important issues of aviation environmental impact. Efforts towards aircraft noise reduction are of paramount importance since noise regulations have become increasingly stringent in order to limit noise levels generated by aircraft.

Aerodynamic noise from landing gears is broadband in nature with distinct narrowband peaks due to coherent turbulent structures associated to extended small components of different sizes (see Guo (2003); Guo *et al.* (2004)). The broadband noise is generated by turbulent flow separation along the blunt elements and the subsequent interaction of the generated turbulent wakes with other elements (see Dobrzynski (2010)). The presence of holes and cavities in the landing gear may introduce additional noise sources including narrowband peaks due to cavity resonance modes (see Casalino *et al.* (2014)).

With current advances in computational power, turbulent flows over blunt bodies can be numerically resolved with significant accuracy. These unsteady flow simulations provide the noise sources which can then be used to predict the far-field noise. However, this hybrid numerical framework using computational fluid dynamics, CFD, coupled to computational aeroacoustics, CAA, is still expensive since large computational grids and accurate algorithms are required to solve not only the small turbulent temporal scales in the numerical simulations but also the low frequency phenomena. These opposing properties increase the simulation time since accurate time marching schemes need to be employed together with low time steps. Furthermore, large datasets need to be stored for an accurate computation of the statistics of the flow and post-processing of the acoustic sources.

In order to better understand the unsteady flow features resolved by the numerical simulations, advanced post-processing tools must be employed to identify the noise sources in the flow. Modal decomposition of the flow is an interesting candidate for such analysis since it may be used to decompose the fluctuation field in modes ranked by energy or frequency, for example, improving the identification of patterns in the flow. These patterns, which are normally associated to coherent structures in phase with each other, radiate noise more efficiently compared to small scale uncorrelated structures present in free turbulence. Hence, the characterization of these elements is crucial to identification of noise sources and to the subsequent development of noise mitigation strategies.

This paper presents numerical simulations of the LAGOON landing gear configuration. This geometry consists of a simplified 2:5 scaled nose landing gear with available database for validation of numerical simulations based on the experiments performed at ONERA facilities by Manoha *et al.* (2008, 2009). Several research groups performed numerical studies of the LAGOON configuration and a database of results was shared in the AIAA-BANC workshops, including

Sanders *et al.* (2011, 2012, 2013); Giret *et al.* (2013); Ribeiro *et al.* (2013); Liu *et al.* (2013); Puente *et al.* (2014); Manoha and Caruelle (2015). These research groups employed different methodologies for the simulations including large eddy simulations and detached eddy simulations using structured and unstructured grids, and low and high-order methods.

## 2. SIMULATION SET-UP

The set-up of the current simulation is briefly described in the following sections. The flow configuration is the same as in the experiments and, hence, the Mach number is set as 0.23, the free-stream temperature, velocity and density are, respectively, 293 K, 99447.7 Pa and 1.18 $^{kg}/_{m^3}$. The perfect gas equation relates pressure to density and temperature while the viscosity is evaluated using Sutherland's law. The Reynolds number is $1.54 \times 10^6$ based on the wheel diameter of 0.3 m.

The Navier-Stokes equations are solved using the Boeing-CFD code, BCFD, with a hybrid methodology which includes the Reynolds Averaged Navier-Stokes solution and Large Eddy Simulation with a modification for delayed transition between the methods, as proposed by Spalart *et al.* (1997, 2006). The DES coefficient is set as 0.65 and the turbulence model in the RANS region is the Spalart-Allmaras (see Spalart and Allmaras (1992)). More details on the code can be seen in Mani *et al.* (2005); Cary *et al.* (2009).

For the time marching scheme, an implicit dual-time step method is employed together with the optimized second-order backward-differencing formulation (BDF2OPT) proposed by Vatsa *et al.* (2010). The BDF2OPT represents a stable blend between a second and a third-order backward difference scheme and, together with the dual-time stepping scheme, they allow for large time steps with both stability and accuracy. Here, the dual-time stepping method solves for 15 cycles in pseudo-time using a line implicit Gauss-Seidel algorithm before advancing a physical time step equal to 10 $\mu s$. Depending on the grid cell, the residual in the pseudo-time may reduce from 1 to 4 orders in the current calculations.

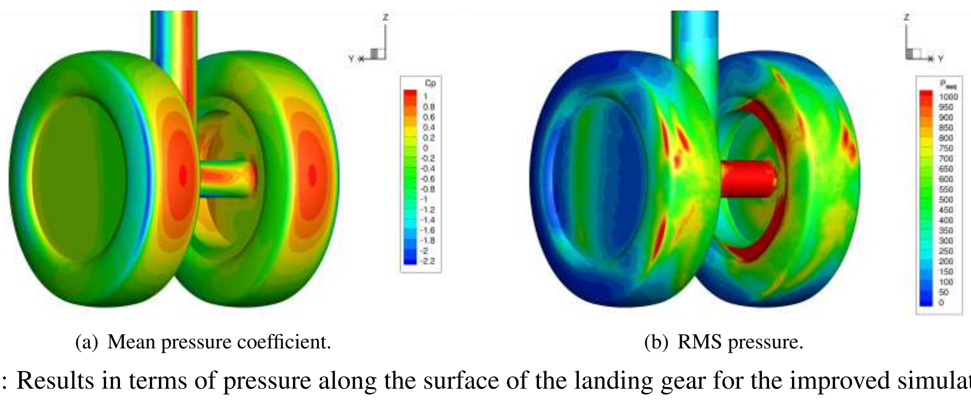
The inviscid flux term is computed using a second order accurate HLLE scheme with a bounded central differencing approach for reduced numerical dissipation of the flux reconstruction. This methodology employs a mixed upwind-central differencing scheme, presented in Winkler *et al.* (2012). The gradient calculation is performed using a least-square method based on cell center values. Also, the Barth & Jespersen flux limiter is employed (see Barth and Jespersen (1989)). For the viscous terms, a full discretization of the Navier Stokes equations are performed using the face-tangent method.

## 3. RESULTS

For the current calculations, a total of 20480 snapshots are used for the statistics, which provide 204.8 ms of physical time. Here, results are presented for velocity measurements in the wake, as well as pressure on the surface. The Proper Orthogonal Decomposition, employed in the context of turbulence by Lumley (1967), is used here to identify coherent structures that are responsible for the tonal noise measured in the experiments. This work is the continuation of that presented by Rodarte Ricciardi *et al.* (2017), where more results are presented.

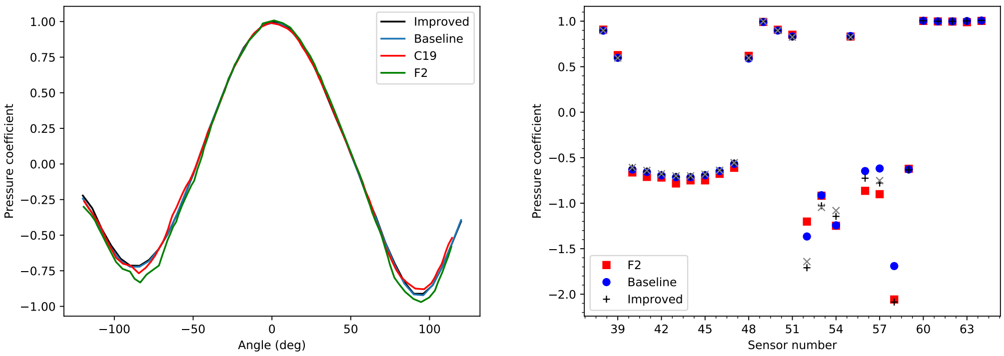
### 3.1 Surface data

The time signal of the pressure along the landing gear surface is stored at every time step, *i.e.*, with a frequency sampling of 100 $kHz$. At first, it is possible to investigate qualitatively the mean pressure as well as unsteady data, in terms of RMS values. These results are shown in Fig. 1, where one can notice that more intense fluctuations are present in the back portion of the axle and wheels, in the edge of the cavity, and in the back and bottom of the cavity. Also, due to the shear layer formed in the shallow cavity in the external face of the wheel, intense pressure fluctuations can also be observed, but with lower amplitudes compared to axle and wheels. In terms of comparison with experiments, Fig. 2 shows good agreement of the computed results compared to the experiments performed by ONERA with two different wind tunnels (Manoha *et al.*, 2008, 2009).



(a) Mean pressure coefficient. (b) RMS pressure.

Figure 1: Results in terms of pressure along the surface of the landing gear for the improved simulation.




(a) Mean pressure coefficient. (b) RMS pressure.

Figure 2: Results in terms of pressure along the surface of the landing gear for the improved simulation.

### 3.2 Wake data

In order to check for a statistically converged flow, we include visualizations of the velocity fields in the wake at plane $z = 0.0m$. Results shown in Figs. 3 and 4 present the three components of velocity, in terms of mean and RMS values.

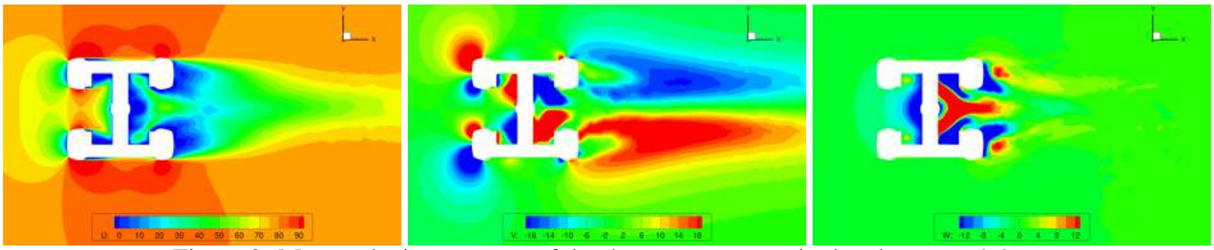


Figure 3: Mean velocity contours of the three components in the plane $z = 0.0m$.

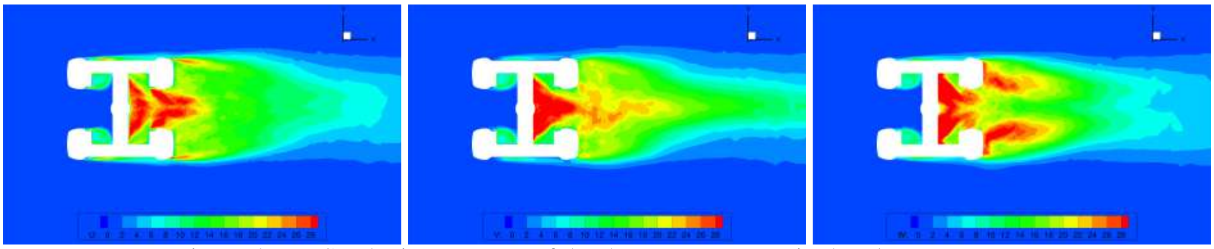


Figure 4: RMS velocity contours of the three components in the plane $z = 0.0m$.

### 3.3 Proper orthogonal decomposition

Proper orthogonal decomposition was first applied in the context of fluid mechanics by Lumley Lumley (1967) to extract coherent structures in turbulent flows. This method is based on the principal component analysis, PCA, a statistical procedure which employs orthogonal transformation to convert a set of $Nt$ observations of correlated variables measured at a time instant $t$ at $Ng$ locations $\vec{x}$ into a set of linearly uncorrelated variables called principal components or modes, $\phi$. Each mode has an associated amplitude coefficient, given by the matrix $A$. By construction, these modes have minimum variance, which makes PCA/POD optimal in terms of reconstruction of the original data if one uses only a few number of modes. It is possible to make the inverse transformation according to

$$U(\vec{x}, t) = \Phi_i(\vec{x}) A(t_i)^T \,, \tag{1}$$

where $A$ is a square matrix with size $Nt$ and $\Phi$ is a rectangular matrix with shape $Ng \times Nt$.

In order to keep this task computationally tractable, one should concatenate the solution at each time step in the form of a column vector of a matrix. This creates the matrix with all observations. Then, one should compute the correlation matrix of the data, being a temporal or spatial correlation based on the size of the measured data. If there are more columns than rows (more time samples than spatial probe locations), as it is generally the case of experiments, one should employ a spatial correlation. In numerical simulations, one should compute the temporal correlation since the number of grid points is usually larger compared to the number of temporal solutions. This latter approach is called the snapshot method, and it was proposed by Sirovich Sirovich (1987). The snapshot method leads to the same results of the classic POD proposed previously by Lumley. For incompressible flows, the data used for the computing the POD correlation matrices is often based on turbulent kinetic energy which is proven to reduce the error in the energy norm. However, for compressible flows, other norms can be employed since thermodynamic variables play an important role in the total energy of the flow.

In this paper, we employ the POD in order to identify possible coherent structures responsible for tonal noise generation in the LAGOON landing gear. With the acquisition of flow data from simulation performed using the improved grid, the temporal correlation matrix $C$ is obtained using a kinetic energy norm as

$$C_{ij} = \sum_{k=1}^{Ng} \left[ u'(x_k, t_i) u'(x_k, t_j) + v'(x_k, t_i) v'(x_k, t_j) + w'(x_k, t_i) w'(x_k, t_j) \right] V_k \; . \tag{2}$$

Here, we have $i$ and $j \leq Nt$, being $Nt$ and $Ng$ the number of snapshots and grid points, respectively. Finally, the singular value decomposition, SVD, of the correlation matrix leads to the singular values $\lambda$, that order the modes by their energy content. Furthermore, the left singular matrix A gives the temporal dynamics of each mode, *i.e.*, the coefficients $a(t)$ of the matrix $A$, computed from

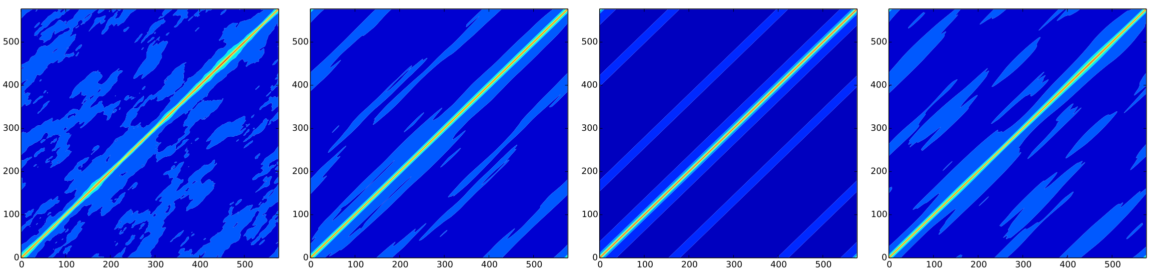
$$CA = \lambda A \; . \tag{3}$$

From this point, the computation of the spatial coefficients is straightforward from

$$\Phi(\vec{x}) = U(\vec{x}, t) A(t) \; . \tag{4}$$

In order to improve the visualization of coherent structures, the spectral POD recently proposed by Sieber *et al.* (2016) is used in this work. The main idea of this method is to filter only the correlation matrix $C$, such that it acts as a spectral filter of the temporal modes $A$ of the standard snapshot POD. The outcome from the SVD of the filtered matrix leads to a preferential band of frequencies in each mode, resulting in "cleaner" spatial modes. The parameters of the SPOD are related to the filter shape or by its half-width, $Nf$, such that its entire width is given by $2Nf + 1$. This parameter cannot be wider than the size of the matrix, $Nt$. Unfortunately, the choice of the parameters in the filtering process of the SPOD is not straightforward and some trial and error is required to achieve the desired results. For example, if one employs a boxcar filter with width equal to the entire size of the matrix and also assumes that the non-filtered correlation matrix is circulant, the result is a Toeplitz matrix. In this case, the eigenvectors (temporal modes) are pure sinusoids and, hence, the spectral POD converges to a discrete Fourier transform. One should keep in mind that this approach is very aggressive and, in order to visualize the dynamic of coherent structures at a frequency band, one should either reduce the filter width or employ a filter with smoother response in the frequency domain.

The main idea in this first assessment of the POD for the LAGOON configuration is to investigate the noise sources in the tonal noise generation by the cavity at 1.5 kHz. Hence, the domain where the correlation is performed includes only the region around the wheel, *i.e.*, inside a cubic box from $-200$ to 200 mm. Also, the number of snapshots $Nt$ is 577, and the time increment between each snapshot is 8x$10^{-5}$ s. Two different filters have been studied, being a Gaussian and a boxcar filter and their half width $Nf$ is either null, 144 or 288. Finally, we assume that the correlation matrix is circulant which is shown to improve the harmonic correlation of the POD modes (Ribeiro and Wolf, 2017). Results for different filtering parameters are shown in terms of the filtered correlation matrix in Fig. 5.

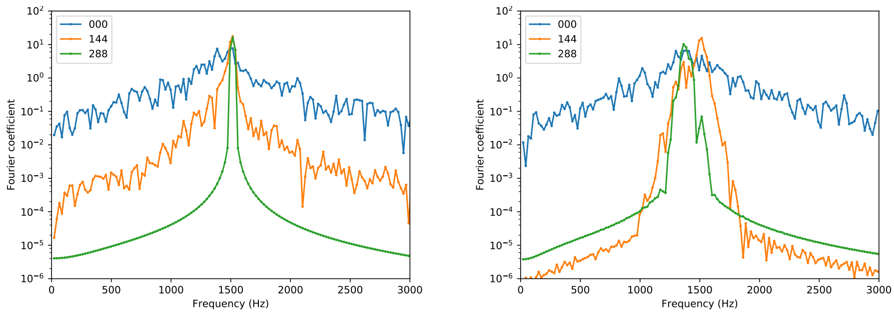


(a) Non-filtered. (b) Boxcar, Nf = 144. (c) Boxcar, Nf = 288. (d) Gaussian, Nf = 144.

Figure 5: Correlation matrix obtained using different filter parameters.

Since the main interest is to find turbulent coherent structures responsible for the tonal noise, a Fourier transform of the temporal modes is required to identify structures excited at 1.5 kHz. After an assessment of the full spectrum of POD modes, we observe that modes 129 and 127 are associated to the target frequency if a boxcar or Gaussian filter are employed, respectively. Results are shown in Fig. 6(a) for the boxcar filter. This approach concentrates all the energy in a single frequency when the filter width has the size of the entire matrix. One should remind that the windowing in the

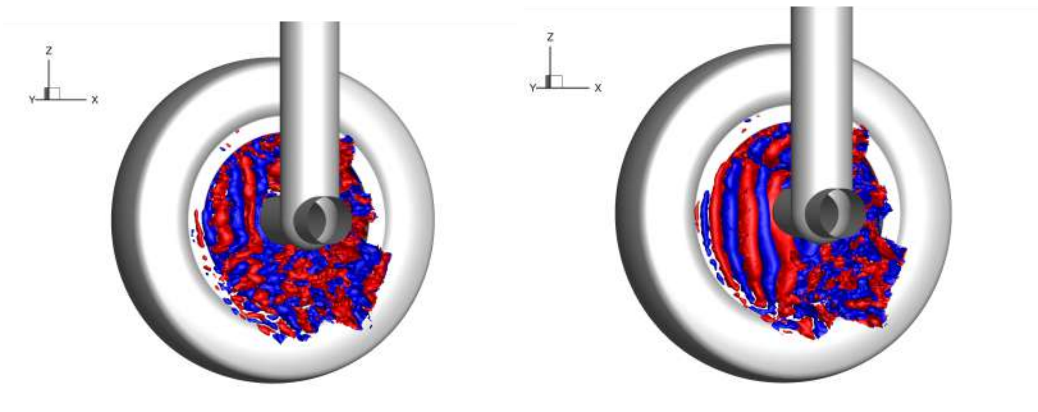
Fourier transform may cause a spectral leakage. On the other hand, results for the Gaussian filter are shown in Fig. 6(b) and one can see that this approach allows a wider response in the frequency domain compared to the boxcar filter due to the response properties of the filters. Therefore, it is possible to obtain the energetic content of a specific mode for a narrow band of frequencies.




(a) Boxcar filter (mode 129). (b) Gaussian filter (mode 127).

Figure 6: Spectral content of temporal modes in the POD of the LAGOON.

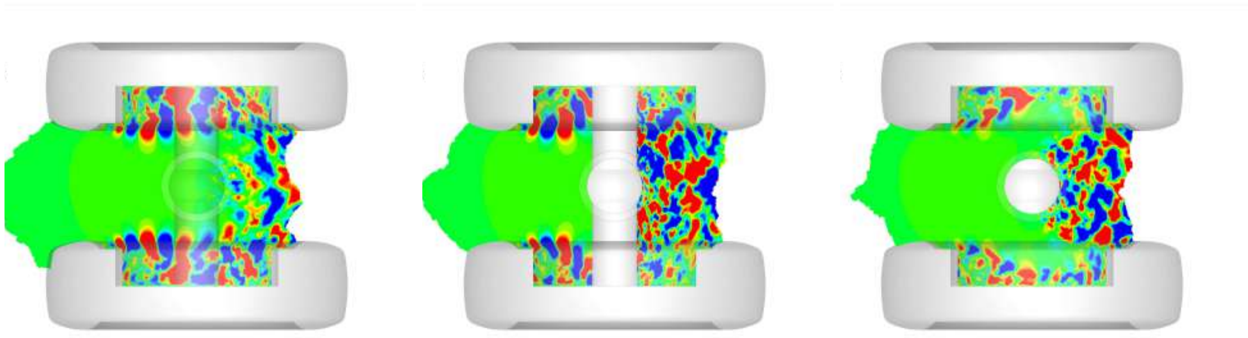
With the computation of the temporal modes, it is possible to obtain the associated spatial eigenfunctions based on Eq. 4. Results using the snapshot method are shown in Fig. 7(a) in terms of iso-surfaces of $v$ velocity fluctuations for the POD mode 129, which is indicated by the blue line in Fig. 6(a). In Fig. 7(b), one can see results in terms of iso-surfaces of $v$ velocity fluctuations using the spectral POD obtained from the orange curve from Fig. 6. With the filtering of the correlation matrix, it is possible to identify quasi two-dimensional coherent turbulent structures with a dominant frequency around 1.5kHz generated at the edge of the cavity. In the snapshot method, the structures are not very well defined. Moreover, there are two dominant frequencies composing such structures based on Fig. 7(a). Since this frequency is associated to the cavity modes (Casalino *et al.*, 2014) of the cavity, these structures are likely to be the noise sources exciting such tones. Since two-dimensional structures are very efficient noise sources, any device that breaks this coherence could lead to a reduction of the tonal noise.



(a) Snapshot POD. (b) Spectral POD.

Figure 7: Iso-surfaces of $v$ velocity fluctuations inside the LAGOON cavity.

Contour plots at different planes normal to the $z$ axis show that the presence of the strut and axle changes the pattern of the coherent structures on the upper portion of the cavity. In Fig. 8(a), one can see that the coherent structures are transported along the cavity possibly reaching the cavity downstream edge. This could lead to the excitation of Rossiter modes in the cavity. Figure 8(b) shows that the axle affects the advection of the coherent structures which impinge on the junction between the bottom of the cavity and the axle, preventing the structures of hitting the downstream edge. Finally, Fig. 8(c) shows that the local acceleration due to the presence of axle and strut changes the dynamics of the structures reducing their spatial correlation for this particular POD mode.



(a) Cut at $z = -33mm$. (b) Cut at $z = 0mm$. (c) Cut at $z = +33mm$.

Figure 8: Contour plots of $v$ velocity fluctuations inside the cavity for 1.5kHz.

## 4. CONCLUSIONS

The current work presents numerical simulations of the AIRBUS-ONERA LAGOON landing gear configuration. Detached eddy simulations are performed and results are shown in terms of mean and RMS values for pressure on the landing gear surface. Comparisons to experimental data show good agreement validating the present methodology.

The use of proper orthogonal decomposition allows the identification of coherent two-dimensional structures in the upstream region of the cavity, along the shear layer. A comparison between the snapshot method and the spectral POD shows that the latter is able to increase correlation of the spectral content with fewer POD modes. This leads to a more defined visualization of the spatial modes and a better identification of coherent structures at specific frequencies. The objective of the current POD and wavelet analysis of the LAGOON landing gear is to identify patterns in the flow that may be associated to frequencies around 1.5kHz and which excite cavity modes. In this context, the presence of the strut and axle changes the pattern of the coherent structures on the upper portion of the cavity. We also observe that, under the axle, coherent structures may reach the downstream edge of the cavity possibly exciting Rossiter modes. In the midplane, the turbulent structures impinge on the junction between the bottom of the cavity and the axle.

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